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David C. Nielsen

USDA-ARS, Central Great Plains Research Station, dcnielsen55@gmail.com

Merle Virgil

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Soil Water Extraction for Several Dryland Crops

David C. Nielsen* and Merle F. Vigil

ABSTRACT

Dryland cropping decisions would benefit from information about soil water extraction by various candidate crops. The objectives of this experiment were to: (i) quantify average soil water extraction by depth in the soil profile for winter wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), proso millet (*Panicum milliaecum* L.), and dry pea (*Pisum sativum* L.), and (ii) verify previously published values of drained upper limit (DUL) and lower limit (LL) of water extraction for each crop grown on a silt loam soil in northeastern Colorado. Soil water contents at planting and physiological maturity were measured over a 21-yr period. Average ending soil water was least at all measurement depths for wheat and greatest for millet. The greatest total profile water extraction was seen for wheat (141 mm) and the least for pea (46 mm). Soil water extraction occurred, on average, from the 0- to 180-cm profile for wheat, 0- to 150-cm profile for corn, 0- to 120-cm profile for millet, and 0- to 90-cm profile for pea. When soil water was plentiful at planting and followed by dry growing season conditions, millet extracted soil water from the entire 0- to 180-cm profile. Crop rotational sequences utilizing shallow rooted crops (such as millet and pea) that do not fully extract soil water at lower depths will allow for greater soil water availability to subsequent crops such as wheat and corn that are able to explore the lower soil profile more effectively for soil water.

Core Ideas

- Crops differ in depth of soil water extraction.
- Crops did not differ in lower limit of water availability.
- Wheat ends the growing season with a drier soil profile.
- Proso millet ends the growing season with a wetter soil profile.
- Extractable available soil water may aid in designing successful rotational sequences.

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GRAIN YIELDS of many crops are highly influenced by amounts of stored soil water (Nielsen et al., 2002, 2009; Nielsen and Vigil, 2005; Lyon et al., 1995; Felter et al., 2006; Schlegel et al., 2018). Consequently, dryland crop rotations that promote effective storage of precipitation and use of stored soil water are likely to be the most successful in the semi-arid production areas of the central Great Plains. Sequencing deep-rooted crops following more shallow-rooted crops may have positive impacts on rotation productivity as unused stored soil water below the rooting zone of a shallow rooted crop becomes available for the subsequent deeper rooted crop. Understanding the rooting characteristics and soil water extraction capacities of various crops could aid in designing effective crop rotations.

Hamblin and Tennant (1987) reported that soil water uptake in wheat and pea in Australia was better correlated with maximum rooting depth than with root length density. Canadell et al. (1996) cited sources that showed a maximum rooting depth of 300 cm for wheat grown on a loamy sand in Western Australia and 240 cm for corn grown in Nebraska. Thorup-Kristensen et al. (2009) found winter wheat grown in Denmark on a sandy loam rooted to a depth of 220 cm, while Kirkegaard and Lilley (2007) reported wheat rooting ranged from 80 to 180 cm in New South Wales, Australia, with year-to-year differences attributable to incomplete soil wetting, soil type, and length of the vegetative period. Kranz et al. (2008) stated that soil water extraction for corn in Nebraska typically followed a conical water uptake pattern of 40, 30, 20, and 10% of total water uptake from the first, second, third, and last one-fourth of total plant-rooting depth. However, this conical soil water uptake pattern could be altered by such factors as plant population; soil physical and chemical properties; water, nutrient, and land management practices; and seasonal precipitation distribution and amount (Irmak and Rudnick, 2014). They reported 68% of water extracted by corn from the 152 cm soil profile

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Abbreviations: DUL, drained upper limit; LL, lower limit of water extraction.

came from the top 61 cm. They also reported that the total rooting depths for corn and wheat were 152 to 182 cm and 122 to 152 cm, respectively, while the effective rooting depths (the depths at which 80 to 90% of soil water extraction and nutrient uptake occur) were 91 to 122 cm and 61 to 90 cm, respectively. Armstrong et al. (1994) found that the maximum soil water extraction depth of six pea varieties ranged from 120 to 200 cm in Western Australia on a deep loamy sand. However, they provided many references to support the often reported statement that pea rooting depth rarely exceeds 100 to 120 cm. They also reported that 80 to 97% of the pea root biomass was located in the surface 20 cm of the soil. Likewise, McKay et al. (2003) stated that pea roots in North Dakota can grow to a depth of 91 to 121 cm with 75% of the root biomass within 61 cm of the soil surface. Fan et al. (2016) fit a modified logistic dose response curve to 21, 7, and 5 published root profile data sets for wheat, corn, and pea, respectively. The results of the curve fitting gave maximum rooting depths of 150 cm for wheat, 118 cm for corn, and 111 cm for pea. They did not provide the soil types used in their analysis, but the data came from five U.S. states, two Canadian provinces, and six other countries. The model also predicted that half of the root biomass could be found in the upper 17 cm of the soil profile for wheat, 14 cm for corn, and 18 cm for pea, and that 95% of the root biomass could be found in the upper 104 cm of the soil profile for wheat, 89 cm for corn, and 85 cm for pea. Both Lyon et al. (2008) and Habiaryemye et al. (2017) stated that proso millet root depth was generally limited to the upper 92 cm of the soil profile, but neither provided data or references to support their statements.

An important quantity for determining available soil water content is the LL of water extraction (Ritchie, 1981; Ratliff et al., 1983). This can be determined observationally by noting the lowest volumetric soil water content measured at the end of a growing season over a period of several years on a given soil type. We previously reported the LL values shown in Supplementary Table S1 that we observed on the Weld silt loam soil (fine, smectitic, mesic Aridic Argiustoll) (https://soilseries.sc.egov.usda.gov/OSD_Docs/W/WELD.html, accessed 11 Jan. 2018) using an earlier, more limited data set from the same study in which the current experiment was conducted (Nielsen et al., 2011). Ritchie (1981) stated that there was evidence (although limited) that annual crop species did not have a very great effect on the LL of deep soils. The DUL was defined by Ratliff et al. (1983) to be the highest field-measured water content of a soil after it had been thoroughly wetted and allowed to drain until drainage became practically negligible. They also defined potentially extractable water as the difference between DUL and LL. The objectives of this experiment were to (i) determine average and maximum soil water extraction by depth in the soil profile for winter wheat, corn, proso millet, and pea, and (ii) verify previously published values of DUL and LL of water extraction for each crop.

MATERIALS AND METHODS

Cultural Practices

Planting dates and hybrids/cultivars used are shown in Table 1 over 21 growing seasons (1997–2017) at the USDA-ARS Central Great Plains Research Station (40°09' N, 103°09' W, 1383 m elevation above sea level) located 6.4 km east of Akron, CO. The long-term experiment was established in the

fall of 1990 and has been previously described by Anderson et al. (1999), Bowman and Halvorson (1997), and Nielsen and Vigil (2010). All rotations employed no-till management where weed control during non-crop periods was accomplished with a combination of contact and residual herbicides. Individual plot size was 9.1 by 30.5 m with East–West row direction. Three replicated plots of each crop were available for soil water measurements each year in a randomized complete block design.

Fertilizer N was applied at planting at rates sufficient to minimize N stress in dryland crops (generally 44–67 kg N ha⁻¹ for wheat and 33–90 kg N ha⁻¹ for corn and millet) based on our experience with the plot area, previous crop yields, and expected weather conditions. Peas received no fertilizer N and were inoculated with the appropriate strain of *Rhizobium* prior to planting.

Soil Water Measurements and Statistical Analysis

Soil water was measured at planting and physiological maturity. Soil water for winter wheat and corn was measured in a winter wheat–corn–fallow rotation while a winter wheat–corn–proso millet–fallow rotation was used for millet soil water measurements and a winter wheat–corn–proso millet–pea rotation was used for pea soil water measurements. Soil water was measured at two locations (separated by about 10 m) near the center of each plot. The measurements were made at 30-cm intervals down the soil profile using a neutron probe (Model 503 Hydroprobe, CPN International, Martinez, CA). The depth intervals were 30 to 60 cm, 60 to 90 cm, 90 to 120 cm, 120 to 150 cm, and 150 to 150 cm, with the neutron probe source centered on each interval. Volumetric soil water in the 0- to 30-cm surface layer was determined using time-domain reflectometry (Trase System I, Soil Moisture Equipment Corp., Santa Barbara, CA) with 30-cm waveguides installed vertically approximately 40 cm from the neutron probe measurement location to average the water content over the entire 30-cm layer. The neutron probe was calibrated against gravimetric soil water samples taken in the plot area. Gravimetric soil water was converted to volumetric water by multiplying by the soil bulk density for each depth. Bulk density was determined from the dry weight of the soil cores (38 mm diam. by 300 mm length) taken from each depth at the time of neutron probe access tube installation.

The volumetric soil water at each of the six depths was averaged over the two locations in each plot to get one value of soil water at each depth in each plot. The soil water extracted from each profile layer was calculated as the difference between beginning and ending volumetric water contents multiplied by the layer thickness (30 cm). The lower limit of water extraction for each crop was determined observationally as the lowest volumetric soil water content observed for each soil layer over the 21 yr of the experiment. Drained upper limit was likewise determined as the wettest volumetric water content observed for each soil layer over the course of the experiment, making sure that at least 3 d had passed since the last precipitation event. Ending volumetric water values for each crop at each measurement depth and total profile soil water extracted were analyzed as a randomized complete block design (using Statistix 10 software, Analytical Software, Tallahassee, FL) to assess significant differences due to crop species. Probabilities that the null hypothesis was true (no difference in ending volumetric water content due to crop species) are reported for each soil water measurement

Table 1. Planting dates, cultivars, and hybrids for winter wheat, corn, proso millet, and pea at Akron, CO.

Crop year	Wheat		Corn		Millet		Pea	
	Planting	Cultivar†	Planting	Hybrid‡	Planting	Cultivar§	Planting	Cultivar¶
1997	30 Sept. 1996	Akron	1 May 1997	Pioneer 3732	19 June 1997	Sunup	1 Apr. 1997	Profi
1998	19 Sept. 1997	Akron	12 May 1998	Dekalb DK493BT	8 June 1998	Sunup	18 Apr. 1998	Profi
1999	22 Sept. 1998	Akron	7 May 1999	Dekalb DK493BT	8 June 1999	Sunup	31 Mar. 1999	Profi
2000	23 Sept. 1999	Akron	10 May 2000	DKC4992	6 June 2000	Sunup	10 Apr. 2000	Profi
2001	29 Sept. 2000	Akron	16 May 2001	NK4242BT	25 June 2001	Huntsman	10 Apr. 2001	Profi
2002	20 Sept. 2001	Akron	15 May 2002	NK4242BT	12 June 2002	Sunup	1 Apr. 2002	Profi
2003	25 Sept. 2002	Akron	21 May 2003	NK4242BT	20 June 2003	Sunup	26 Mar. 2003	Profi
2004	19 Sept. 2003	Akron	3 June 2004	N42B7	7 June 2004	Sunup	26 Mar. 2004	Profi
2005	27 Sept. 2004	Akron	18 May 2005	N42B7	7 June 2005	Sunup	8 Apr. 2005	Profi
2006	21 Sept. 2005	Akron	6 May 2006	N42B7	8 June 2006	Huntsman	17 Apr. 2006	Profi
2007	27 Sept. 2006	Danby	25 May 2007	N42B7	21 June 2007	Huntsman	11 Apr. 2007	DS-Admiral
2008	27 Sept. 2007	Danby	19 May 2008	N42B7	20 June 2008	Huntsman	5 Apr. 2008	DS-Admiral
2009	26 Sept. 2008	Danby	1 June 2009	N42B7	29 June 2009	Huntsman	23 Apr. 2009	DS-Admiral
2010	29 Sept. 2009	Snowmass	18 May 2010	GH7891CB/LL	1 June 2010	Huntsman	12 Apr. 2010	DS-Admiral
2011	24 Sept. 2010	Snowmass	10 May 2011	NuTech 1H979	9 June 2011	Huntsman	4 Apr. 2011	DS-Admiral
2012	26 Sept. 2011	Snowmass	10 May 2012	PH 500	30 May 2012	Huntsman	10 Apr. 2012	DS-Admiral
2013	2 Oct. 2012	Snowmass	16 May 2013	PH 5140	3 June 2013	Huntsman	8 Apr. 2013	DS-Admiral
2014	2 Oct. 2013	Brawl CL Plus	16 May 2014	PH 5140	5 June 2014	Huntsman	21 Apr. 2014	DS-Admiral
2015	29 Sept. 2014	Brawl CL Plus	3 June 2015	PH 5140	25 June 2015	Huntsman	8 Apr. 2015	DS-Admiral
2016	1 Oct. 2015	Brawl CL Plus	20 May 2016	PH 5140	16 June 2016	Huntsman	5 Apr. 2016	DS-Admiral
2017	27 Sept. 2016	Brawl CL Plus	25 May 2017	PH 5140	12 June 2017	Huntsman	5 Apr. 2016	DS-Admiral
Average	26 Sep		18 May		13 June		8 Apr.	

† Akron and Brawl CL Plus are hard red winter wheat cultivars; Danby and Snowmass are hard white winter wheat cultivars; planting rate varied from 66 to 73 kg ha⁻¹

‡ Pioneer 3732 (101 d); Dekalb DK493BT (99 d); DKC4992 (99 d); NK4242BT (99 d); N42B7 (99 d); GH7891CB/LL (103 d); NuTech 1H979 (97 d); PH 400 (90 d); PH 5140 (91 d); planting rate was 34,580 seeds ha⁻¹ (1997–2002) and 29 640 seeds ha⁻¹ (2003–2017).

§ Sunup and Huntsman are white-seeded proso millet varieties; planting rate was 17 kg ha⁻¹

¶ Profi and DS-Admiral are semi-leafless yellow pea varieties; planting rate was 134 kg ha⁻¹ (1997–1999) and 202 kg ha⁻¹ (2000–2017).

depth. Significant differences in total profile soil water extraction due to crop species were determined based on Tukey's HSD (0.05) mean separation test.

RESULTS

Precipitation

Annual precipitation over the course of the experiment was highly variable (Table 2), ranging from 228 mm in 2012 to 629 mm in 2014. The average precipitation over the course of the experiment (408 mm) was nearly the same as the 110-yr average precipitation (419 mm). Precipitation for the winter wheat growing season averaged 254 mm and ranged from 131 mm (2002) to 393 mm (2011). Precipitation for the corn growing season averaged 221 mm and ranged from 76 mm (2012) to 354 mm (1999). Precipitation for the millet growing season averaged 142 mm and ranged from 42 mm (2003) to 275 mm (2014). Precipitation for the pea growing season averaged 165 mm and ranged from 38 mm (2012) to 315 mm (2011).

Soil Water Extraction

The average soil water extracted (Fig. 1, top panel) was significantly different among the four crops. The greatest amount of soil water was extracted by wheat (144 mm), followed by corn (122 mm), millet (92 mm), and pea (47 mm). Depth of water extraction was also similarly different among the four crops. Wheat extracted soil water from the entire 0- to 180-cm soil profile, with 67% coming from the 0- to 90-cm soil profile. Corn extracted soil water mainly from the 0- to 150-cm soil

profile, with 77% coming from the 0- to 90-cm soil profile. Millet extracted soil water mainly from the 0- to 120-cm soil profile, with 81% coming from the 0- to 90-cm soil profile. Nearly 100% of the soil water extracted by pea came from the 0- to 90-cm soil profile.

Soil water extraction is influenced in part by rooting capacity of the crop (which may be strongly influenced by growing season length), the amount of soil water available at planting, and the timing and amount of growing season precipitation. To more accurately determine differences in the capacity of the four crops to extract water from this silt loam soil, we identified a single growing season for each of the four crops that had a wet soil water profile at planting followed by a dry growing season. The same relative pattern in soil water use (Fig. 1, bottom panel) was seen for wheat, corn, and pea, but with greater overall soil water extraction compared with the average values shown in the top panel. The wheat year that resulted in the greatest soil water extraction (2002) occurred when volumetric water content in the upper and lower 90 cm halves of the soil profile averaged 0.289 m³ m⁻³ and 0.207 m³ m⁻³, respectively, and growing season precipitation was 131 mm (49% of the long-term average). In that year, wheat extracted 221 mm of soil water, with water being extracted from all six measurement depths in the 0- to 180-cm soil profile. During the corn growing season in 2015, the volumetric water content in the upper and lower 90 cm halves of the soil profile averaged 0.294 m³ m⁻³ and 0.191 m³ m⁻³, respectively, and the growing season precipitation was 145 mm (57% of the long-term average). In that year corn extracted 188

Table 2. Annual precipitation and growing season precipitation for winter wheat, corn, proso millet, and pea at Akron, CO, 1997 to 2017, and long-term precipitation averages.

Year	Annual precipitation	Wheat†	Corn	Millet	Pea
		mm			
1997	379	200	274	116	148
1998	304	166	180	160	56
1999	498	244	354	228	216
2000	355	137	161	128	70
2001	438	283	201	123	161
2002	238	131	137	96	74
2003	430	383	216	42	281
2004	401	218	327	160	157
2005	491	266	304	212	225
2006	325	211	169	68	73
2007	354	226	177	137	91
2008	521	249	332	233	125
2009	482	351	244	178	206
2010	306	245	150	138	169
2011	439	393	263	138	315
2012	228	151	76	67	38
2013	401	177	216	117	103
2014	629	338	352	275	237
2015	469	291	145	145	263
2016	469	371	221	140	236
2017	417	298	140	90	213
Average	408	254	221	142	165
1908–2017	419	265	253	169	179

† Because winter wheat is typically planted in September, growing season precipitation accrues beginning in September or October in the year previous to the year designated in the first column, which is the year of harvest.

mm of soil water, mostly from the 0- to 150-cm layer of the soil profile. During the pea growing season in 2010, the volumetric water content in the upper and lower 90 cm halves of the soil profile averaged $0.277 \text{ m}^3 \text{ m}^{-3}$ and $0.171 \text{ m}^3 \text{ m}^{-3}$, respectively, and the growing season precipitation was 169 mm (94% of the long-term average). Even with nearly average precipitation in 2010, pea extracted 119 mm of soil water, mostly from the 0- to 120-cm layer of the soil profile. This was the most water extracted by pea during the 21 yr of the study. All three of these crops extracted water from the soil profile in the same relative manner as seen for the average soil water extraction data in the top panel of Fig. 1, but in greater amounts.

Under these conditions of a wet starting soil water profile followed by a dry growing season, we found that millet did not extract water in the same way relative to the other crops as shown in the top panel of Fig. 1. During the millet growing season in 2003, the volumetric water content in the upper and lower 90 cm halves of the soil profile averaged 0.323 and $0.300 \text{ m}^3 \text{ m}^{-3}$, respectively, and the growing season precipitation was 42 mm (25% of the long-term average). In that year, with a soil profile that was almost uniformly near field capacity at all six measurement depths and with only 7 mm of precipitation during the last 20 d of growth, millet extracted an amazing 257 mm of soil water (279% greater than the 21-yr average), coming from all six measurement depths in the 0- to 180-cm soil profile.

From the 1997 to 2017 average soil water extraction data (Fig. 1, top panel), we inferred that the average active root zones for winter wheat, corn, millet, and pea were 180, 150, 120, and

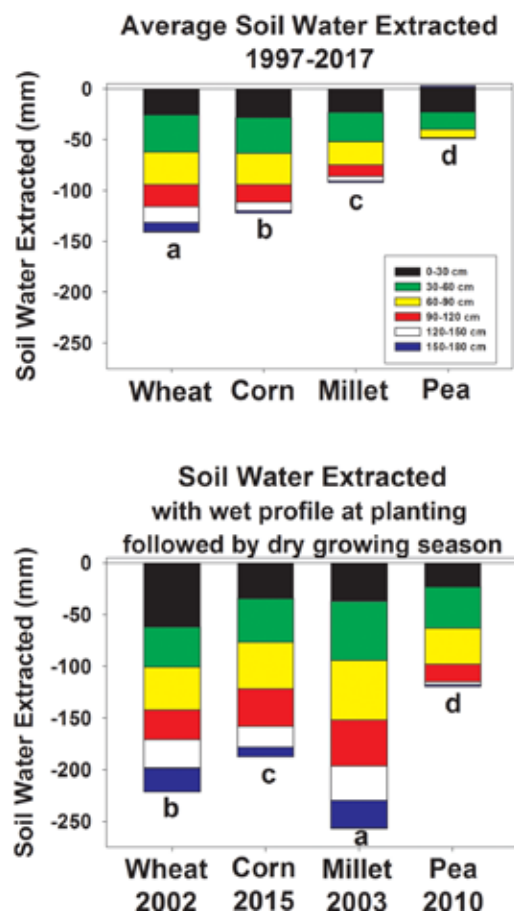


Fig. 1. (top) Average soil water extracted by winter wheat, corn, proso millet, and pea grown on a silt loam soil at Akron, CO, from 1997 to 2017; and (bottom) soil water extracted by these crops during years with a wet soil profile at planting followed by a dry growing season. Different letters below the bars within a given panel indicate significantly different total soil water extraction amounts based on Tukey's HSD (0.05).

90 cm, respectively. As mentioned earlier, Kranz et al. (2008) stated that soil water extraction for corn in Nebraska typically followed a conical water uptake pattern of 40, 30, 20, and 10% of total water uptake from the first, second, third, and last one-fourth of total plant-rooting depth. We divided the active root zones stated above into fourths and calculated the percentage of total water extraction for each fourth of the root zone to determine if water extraction followed a similar conical water uptake pattern for each of the four crops. We did not observe 40% of the total extraction in the top fourth, but rather 31% for wheat and corn, 27% for millet, and 35% for pea (Fig. 2). In the second one-fourth of the root zone we calculated values close to the 30% reported by Kranz et al. (2008), with values ranging from 30% for pea to 36% for wheat. For the third one-fourth of the root zone we calculated values close to the 20% reported by Kranz et al. (2008), with values ranging from 21% for wheat to 26% for millet. And for the bottom fourth of the root zone we calculated values ranging from 11% for corn to 14% for wheat. So except for the top fourth of the root zone, values were close to the conical distribution that Kranz et al. (2008) reported for corn.

Ending Volumetric Water Profiles

The average volumetric soil water profiles at physiological maturity are shown in Fig. 3. At all six measurement depths,

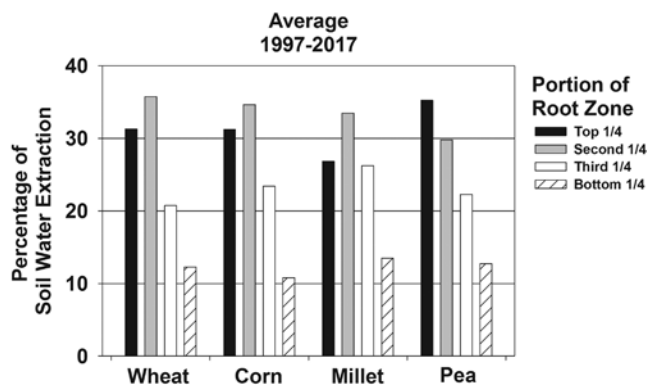


Fig. 2. Average soil water extracted by winter wheat, corn, proso millet, and pea grown on a silt loam soil at Akron, CO, from 1997 to 2017 as expressed as a percentage of total water extracted for the active root zone divided into fourths. The active root zone was 0 to 180 cm for winter wheat, 0 to 150 cm for corn, 0 to 120 cm for proso millet, and 0 to 90 cm for pea.

volumetric water was lowest for winter wheat. However the differences in soil water in the top layer (0–30 cm) due to crop were not significant ($P = 0.06$). In the 30- to 60-cm layer, the average water content for wheat was significantly drier than for the other three crops, which were all statistically the same. In the 60- to 90-cm and 120- to 150-cm layers, millet had the greatest water content compared with the other three crops, which were all statistically the same. In the 90- to 120-cm layer, millet again had the greatest ending soil water content, which was not different from the water content for pea, but was significantly greater than the water content for wheat and corn. This layer showed the driest average ending water content for all four crops. For the 150- to 180-cm layer, there was again a significant effect of crop on ending water content ($P = 0.01$), but corn, pea, and millet were statistically the same, and corn, pea, and wheat were statistically the same. The average total profile water at physiological maturity was 227, 253, 274, and 253 mm for wheat, corn, millet, and pea, respectively.

As we noted earlier, there were differences in the average depth of water extraction among the four crops. We show those average depths with the horizontal dotted lines in Fig. 3 in order that the reader might be aware that these average ending water contents below the zone of active water extraction are related to the soil water extraction of the previous crops in the rotation and the differing effects of those previous crop residues on evaporation suppression and snow catch. For example, with pea only extracting water on average from the 0- to 90-cm soil profile, the ending water contents below 90 cm for pea (that are similar to corn) are the result of pea being in the winter wheat–corn–proso–pea rotation. The water use of the previous crops and precipitation storage characteristics of those previous crop residues during non-crop periods are the more important factors influencing ending volumetric water content for pea at those lower depths rather than water extraction by pea.

Drained Upper Limit

The previously published values of DUL (Nielsen et al., 2011) obtained on this silt loam soil are shown in Fig. 4, top panel, and the actual values are given in Supplementary Table S2. In addition to these values, Fig. 4 also shows the wettest volumetric water content values observed in this experiment over the 1997

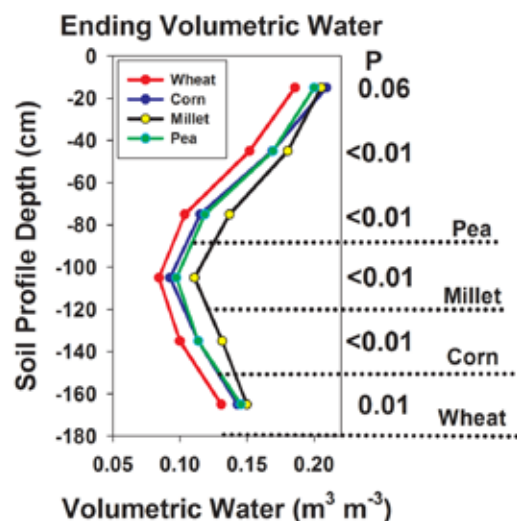


Fig. 3. Average (1997–2017) volumetric water at physiological maturity for winter wheat, corn, proso millet, and pea on a silt loam at Akron, CO. P values on right side are the probability that the null hypothesis is true that there is no difference in volumetric water due to crop at that particular depth. Horizontal dotted lines labeled Pea, Millet, Corn, and Wheat to the right of the figure designate the average depth of soil water extraction determined in this study.

to 2017 period, and those values are also given in Supplementary Table S2. It is readily evident that those observed wettest water contents are much greater than the DUL values previously reported. We thought that perhaps these wettest values had been obtained during periods when not enough time had passed after large precipitation events to allow for drainage to be complete. Ratliff et al. (1983) stated that it might take from 2 to 20 d after a wetting period in order for drainage to essentially stop so that a valid DUL could be obtained. That may have been the case for the 0- to 30-cm layer as 38 mm of rain had fallen in the 7 d prior to the soil water measurement on 30 June 1997. However, the values in the second, third, fifth, and sixth layers below the soil surface that were observed on 9 July 2003 are probably valid estimates of the DUL in these lower depths as only 11 mm of rain had fallen 2 d prior to this measurement in growing millet and only 16 mm had fallen 10 d prior to the measurement. The value for the fourth layer below the soil surface was measured on 16 Oct. 2009 and also is likely a valid estimate of DUL for that layer as only 1 mm of precipitation fell on both 1 and 3 d prior to the measurement and a total of only 6 mm fell during the 8 d prior to the measurement.

Because the values of DUL based the wettest observed volumetric water contents were so much greater than we had previously published and when used in conjunction with average LL values (that we will discuss later) produced anomalously high plant available water holding capacities for this silt loam soil, we decided to try an alternative approach to determining DUL by plotting a cumulative probability exceedance graph of all of the volumetric water values obtained at planting for all four crops over the 21 yr of the experiment (Supplementary Fig. S1). From the figure, we obtained values of volumetric water content such that 95% were drier and only 5% were wetter. Those values are given in Supplementary Table S2 and shown in Fig. 4 (top panel). Those values were seen to be nearly the same as previously reported for the second, fourth, fifth, and sixth

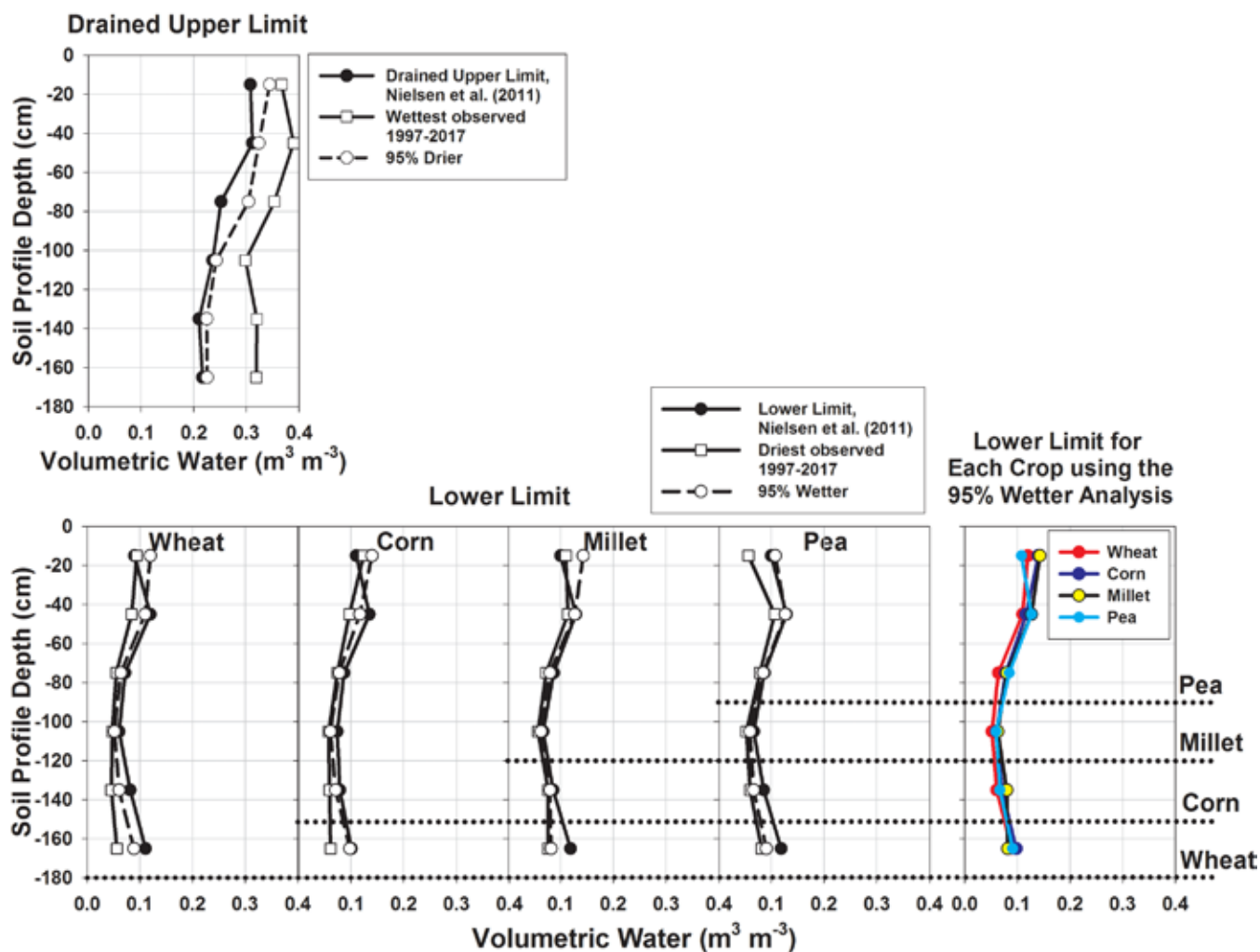


Fig. 4. (top) Drained upper limit of soil water content and (bottom) lower limits of water extraction for a silt loam soil at Akron, CO. Lines with solid black circles are from previously published data. Lines with open squares are from wettest or driest observed values over the 1997 to 2017 period. Dashed lines with open circles are from the cumulative probability exceedance graphs (Supplementary Fig. S1 and S2). Horizontal dotted lines labeled Pea, Millet, Corn, and Wheat to the right of the lower panel designate the average depth of soil water extraction determined in this study.

measurement layers and between the previously reported DUL and the wettest observed water contents for the first and third layers. These values of volumetric water content developed from Supplementary Fig. S1 are more conservative estimates of DUL than the wettest soil water content values measured several days after precipitation. The wettest values measured have the potential of being outlier data. These values developed from Supplementary Fig. S1, take into account an actual probability of occurring that is toward the wet end of the measured data with a slightly higher frequency of expected occurrence than the wettest observed water content.

Lower Limits of Water Extraction

We performed a similar analysis for determination of LL as we did for DUL, that is, comparison of previously published LL values (Nielsen et al., 2011) against LL determined as the lowest volumetric water content observed over the 21 yr of the study and against the volumetric water contents for which 95% were wetter and only 5% were drier (see Supplementary Fig. S2 for the cumulative probability exceedance graphs). Those results are shown in Fig. 4 (lower left four panels) with numeric values given in Supplementary Table 1. The three methods of determining

LL produced similar results. The most noticeable differences are slightly higher LL values when calculating LL through use of the probability exceedance graphs from Supplementary Fig. S2. The three methods did not produce LL values that were greatly different for the four crops (Fig. 4). We show those values compared by crop in Fig. 4, lower right panel, as determined by the analysis method that identified the value for which 95% of the ending volumetric water contents were wetter and only 5% were drier. When those values were averaged for all four crops we obtained LL values by depth (surface to lowest measurement layer) of 0.128, 0.120, 0.077, 0.059, 0.070, and 0.090 $\text{m}^3 \text{m}^{-3}$.

As with Fig. 3, we show the average depths of soil water extraction, as determined for the four crops in this study, with horizontal dotted lines. The important result to note here is that even though there are distinct differences in depth of water extraction by these four crops, use of the same LL values noted above for all four crops appears to be justified.

Plant Available Water

Plant available water is generally defined as the difference between field capacity and wilting point (Ritchie, 1981). Ratliff et al. (1983) defined potential extractable soil water, essentially

plant available water, as the difference in water content between DUL and LL. Using this definition, we calculated the plant available water (Table 3) using the averaged LL values given at the end of the previous section and using previously published DUL values (Nielsen et al., 2011) as well as using DUL values estimated by both the wettest observed volumetric water contents and the water contents that were obtained from the cumulative probability exceedance graph when 95% of the values were drier and only 5% were wetter (Supplementary Fig. S1 and Fig. 4). Using the previously published DUL values, plant available water ranged from 38 mm (150–180 cm layer) to 57 mm (30–60 cm layer) of water per 30 cm of soil and totaled 297 mm for the 180-cm soil profile. Using the wettest observed values as the DUL gave plant available water for the six measurement depths that ranged from 69 mm of water per 30 cm of soil (150–180 cm layer) to 83 mm of water per 30 cm of soil (60–90 cm layer) and totaled 452 mm for the 180-cm soil profile. These values of plant available water were much greater than when the calculation was made using the DUL defined by the 95% drier/5% wetter criterion. In that case the plant available water ranged from 41 mm of water per 30 cm of soil (150–180 cm layer) to 68 mm of water per 30 cm of soil (60–90 cm layer) and totaled 336 mm for the 180-cm soil profile.

DISCUSSION

Winter wheat, corn, proso millet, and pea, four commonly used crops in dryland crop rotations in the central Great Plains, were different in the average volumetric water content observed at the end of the growing season (Fig. 3). Average ending soil profile water contents following wheat production were generally drier than after millet production at all measurement depths. The average soil water extracted was greatest for wheat followed by corn and millet and least for pea (Fig. 1). Average depth of rooting could be estimated as 180 cm for wheat, 150 cm for corn, 120 cm for millet, and 90 cm for pea. This contrasts with the report of Irmak and Rudnick (2014) of greater rooting depth for corn than for winter wheat in eastern Nebraska.

When our soil water extraction data set was analyzed by dividing the active root zone into fourths, we did not observe 40% of total water extraction coming from the top one-fourth of the soil profile as Kranz et al. (2008) did for corn in eastern Nebraska. Our observation for corn water extraction was 31% for the top fourth of the active root zone. However, water extraction in the bottom three-fourths of the soil profile did follow the conical pattern described by Kranz et al. (2008) (Fig. 2). The difference in the water extraction in the top fourth of the soil profile is likely attributable to differences in soil water contents at planting and water stress conditions between eastern Nebraska and eastern Colorado. Kranz et al. (2008) stated that the conical water extraction pattern for corn was typical under non-stressed water and nutrient conditions. Corn grown under dryland conditions in semiarid eastern Colorado rarely grows under non-stressed water conditions.

Because of the variability in timing and amount of precipitation in conjunction with previous crop water use, only the millet crop may have had a year that truly allowed us to see the rooting potential and maximum soil water extraction of the crop (Fig. 1, bottom panel). The other three crops never experienced a year in which the lower half of the measured soil profile

Table 3. Plant available water holding capacity determined as the difference between the lower limit of soil water extraction (averaged across four crops) and three estimates of drained upper limit (DUL) for a silt loam soil at Akron, CO.

Soil layer	Using previously published DUL	Using observed wettest soil water content	Using DUL based on 95% drier, 5% wetter†
cm	mm water per 30 cm soil		
0–30	54	72	65
30–60	57	81	61
60–90	53	83	68
90–120	53	72	55
120–150	42	75	46
150–180	38	69	41
Total	297	452	336

† See Supplementary Fig. S1.

was filled to field capacity at planting. In particular, we did not have the same kind of very wet starting soil water conditions in the lower half of the soil profile at pea planting that we had at millet planting to ascertain what the true limit would be for pea roots to explore the lower depths of the soil profile for water. In 2010 we observed the wettest soil profile for pea, but growing season precipitation was high (94% of the long-term average). We therefore probably did not have the conditions available to see the true potential for pea roots to extract soil water.

It was a rather surprising result to observe proso millet as having extracted 257 mm of water out of the entire 0- to 180-cm soil profile in 2003 (Fig. 1, bottom panel) when planted into a very wet soil profile followed by a dry growing season. Millet is often described as a shallow rooted crop (Baltensperger, 1996; Lyon et al., 2008; Habiyaemye et al., 2017). And while that statement appears to be confirmed by the average water extraction observed in this study (Fig. 1, top panel), it appears that this is not always the case, and that millet does have the capacity to explore and extract water from much deeper in the soil profile when water is readily available and growing season conditions demand its uptake. This capacity to occasionally extract available water from deep in the soil profile provides additional support for the statements made regarding proso millet being a crop highly adapted to the semiarid Great Plains (Baltensperger, 1996; Lyon et al., 2008). However, the average water extraction by millet (Fig. 1, top panel) of 92 mm primarily from the 0- to 120-cm soil profile supports the conclusion of Lyon et al. (2008) that millet can be used effectively as a rotation crop following sunflower (*Helianthus annuus* L.) when soil water in the lower half of the soil profile is likely to be depleted (Lyon et al., 2008).

The plant available water holding capacity values (Table 3) determined as the difference between the maximum observed volumetric water contents (Supplementary Table S2) in each of the six layers of the 0- to 180-cm soil profile and the corresponding LL based on the 5% drier/95% wetter cumulative probability distribution of soil water contents at physiological maturity (Fig. 4, lower right panel) were much greater for the silt loam soil used in this study (69–83 mm per 30-cm soil layer, Table 3) than typically reported for a silt loam (50–63 mm per 30-cm soil layer; Ball, 2001). The plant available water holding capacity values calculated with a DUL based on 95% drier/5% wetter cumulative probability distribution (41–68 mm) were much closer to the values presented by Ball (2001).

We found that LL values determined in this study were not greatly different among the four crop species. Therefore, values averaged across crop species are likely appropriate to use when determining plant available water at planting for making crop choice selections in flexible cropping systems. However, although we have not presented data in this study regarding the LL values for sunflower, we remain confident that the LL values in the lower half of the soil profile published by Nielsen et al. (2011) that are much lower for sunflower than for other crops is a valid result. Consequently, the average LL values presented in this current study would underestimate plant available soil water at planting for sunflower. Additionally, when calculating plant available water contents prior to planting, producers should be using the average profile water extraction depths found in this study which did vary by crop species (180 cm for wheat, 150 cm for corn, 120 cm for millet, 90 cm for pea).

CONCLUSION

Twenty-one years of soil water data at planting and physiological maturity were used to evaluate soil water extraction amounts and to infer rooting depths of dryland winter wheat, corn, proso millet, and pea on a silt loam soil in semiarid eastern Colorado. Average soil water extraction was in the order (greatest to least) of wheat, corn, millet, and pea. Inferred rooting depth followed the same order. Likewise, soil water remaining in the soil at physiological maturity followed the order of wheat < corn = pea < millet. Volumetric water at physiological maturity was least for all four crops in the 90- to 120-cm soil layer.

Determinations of LL for all four crops by both observation of the lowest volumetric water content over the 21 yr of the experiment and by noting the volumetric water content at physiological maturity for which 95% of the observations were wetter and only 5% were drier produced nearly the same result. Also, the LL values were not greatly different among the four crop species. The DUL values determined from the wettest volumetric water contents observed at planting after allowing sufficient time for drainage to occur produced values much wetter than previously published for this soil (0.299–0.390 m³ m⁻³). Using these DUL values with the LL values determined in this study gave plant available water holding capacity values that were much larger than generally reported for silt loam soils. Using a cumulative probability exceedance graph of volumetric water content at planting over the 21 yr of the experiment to define DUL as the water content for which 95% of the observations were drier and only 5% were wetter produced a more conservative estimate of plant available water holding capacity that was similar to previously published values (41–68 mm per 30-cm soil layer).

While the soil water extraction amounts and depths of inferred rooting presented in this paper can serve as guidelines for designing rotational sequences that can best take advantage of existing available soil water at planting and for making crop selections for flexible cropping systems based on available soil water at planting, readers should be aware that rooting depths and soil water extraction can vary widely from year to year based on available water at planting, growing season temperatures, evaporative demand, and precipitation amounts and timing. Consequently, the LL values defined in this study used in conjunction with measured soil water at planting will only produce approximations of plant available water that, depending on

actual root development, may or may not be used by the plant during the growing season.

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SUPPLEMENTAL MATERIAL

Fig. S1. Cumulative probability exceedance graphs for volumetric water contents at planting for winter wheat, corn, proso millet, and pea grown on a silt loam soil at Akron, CO, from 1997 to 2017. The solid horizontal line shows the water contents for which the probability of a drier soil was 95% (5% of observed water contents were wetter).

Fig. S2. Cumulative probability exceedance graphs for volumetric water contents at physiological maturity for winter wheat, corn, proso millet, and pea grown on a silt loam soil at Akron, CO, from 1997 to 2017. The solid horizontal line shows the water contents for which the probability of a wetter soil was 95% (5% of observed water contents were drier).

Table S1. Lower limits of volumetric soil water for winter wheat, corn, proso millet, and pea on a Weld silt loam, Akron, CO, as previously published and as determined by the lowest observed water content from 1997 to 2017 and the observed value for which 5% were drier and 95% were wetter.

Table S2. Drained upper limits of volumetric soil water for a Weld silt loam, Akron, CO, as previously published and as determined by the wettest observed water content from 1997 to 2017 and the observed value for which 5% were wetter and 95% were drier.

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